NASA-CR-166682

DATA ANALYSIS FOR THE HARD X-RAY EXPERIMENT ON BOARD THE ANS SPACECRAFT

FINAL REPORT

NASA Contract NAS5-23282

MARCH 1978

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
Greenbelt, Maryland 20771

Prepared by

Smithsonian Institution
Astrophysical Observatory
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The Smithsonian Astrophysical Observatory
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I. INTRODUCTION

The Astronomical Netherlands Satellite (ANS) was launched on 30 August 1974, and operated continuously until 11 December 1975. At that date normal pointing observations ceased and the satellite was left in continuous scanning mode. Not withstanding these scanning observations, ANS obtained ~ 3 times the original anticipated amount of data. A number of exciting new results were obtained, in particular, the remarkable new discovery of X-ray bursts from globular clusters. This latest new phenomena prompted a resumption of the ANS operations from 1 March 1976 until 20 April 1976, to investigate systamatically X-ray emission from a selected group of globular clusters, plus some other objects known by then to have been X-ray burst emitters. After 20 April 1976 the satellite was again left in the scanning mode until 1 July 1976. The ANS Hard X-ray Experiment (HXX) design, its operation, and inflight calibration were published soon after launch.[1] The scientific objectives considered in both planning and analyzing the observations were:

A. The measurement of the spectra of X-ray sources in the energy level 1 to 30 keV.

B. The observation of both periodic and flare-type time variation in X-ray objects; search for new periodicities in the entire range from msec to $\sim$ 2 days.

C. The detection of faint sources and the refinement of locations of certain sources.

D. The detection of silicon line emission (1.86 and 2.00 keV).

E. The observation of the surface brightness of extended sources by scanning with the slit field of view.

F. The measurement of X-ray sources simultaneously with correlated ground-based optical and radio observations.

Most of these objectives were achieved and the results were published in the literature. We summarize here these results as the final report of contract NAS5-23282.

II. SUMMARY OF DATA ANALYSIS RESULTS

A. Galactic Sources

Our first analysis projects concentrated on the Cygnus X-1 and X-3 sources since the data from these were among the first obtained in relatively complete form.

Cyg X-1 was observed in November 1974 to be at nearly the same level of intensity as had been reported since April 1971. A number of sharp dips in intensity were observed at several predicted phases of the binary system. Such dips had previously been seen by other experiments, but not as frequently or in such detail as were observed by ANS.[2] During the second observing period of May 1975, an important discovery was made by HXX: Cyg X-1 was, presumably for the first time, undergoing an upwards transition in intensity to the level before the March 1971 downwards transition.[3] Since this event (duration ~ 1 month), a second similar event was discovered[4] by HXX/SXX in November 1975 which according to other satellite experiments, lasted until early 1976. Detailed spectra were obtained from all three observations and are of special significance in being recorded with the same instrument during both low and high states of the source.[5]

Cygnus X-3 was observed in November 1974 and in May and November 1975. The data obtained have yielded important new results.[6] The 4.8-hour period has been determined to a greater precision than ever before and significant limits have been placed on possible long-term period changes.[7] Intensity and spectral changes were found on a time scale of months. The time fluctuation studies in the time range of several seconds to 0.5 days have shown significant intensity fluctuations. In particular, large flux variations were observed on a time scale of 1 to 2 binary periods. In particular, large flux variations were observed on a time scale of 1 to 2 binary periods (4.8 - 9.6 hours) especially at light curve maxima. Together with the faster time intensity fluctuations, these observations have suggested a new model for this source. Finally, the HXX spectrometer detected an anomolous flux intensity at 6.7 keV, which had been reported by several satellite experiments and which can be interpreted as line emission from highly ionized iron atoms.[8]

The other group of galactic sources for which data had been analyzed in detail are the globular cluster X-ray sources. Extensive observations of the two brightest sources, 4U 1820-30 assoceated with NGC 6624, and 4U1746-37 (NGC 6441), were conducted in March and September 1975. A fundamental new discovery in X-ray astronomy was made from analysis of the HXX data on 4U 1820-30:[9,10,11,12,13] two intense (factor of ~25), fast (~0.5 sec rise, ~10 sec exponential decay) bursts of X-rays were detected within an 8-hour period while observing this source on 28 September 1975. The bursts were confirmed by SXX and represent a totally new type of time variation or type of X-ray source. They have since been reported by several other satellite experiments. The HXX discovery detection remains especially significant since the two 10' x 3° LAD detectors, mutually offset by 4', determined the

burst directions to be within 1' in declination of 4U 1820-30, and the ratio of HXX/SXX counts limited the uncertainty in right ascension to within ~ 30' of this globular cluster source. Assuming then that the bursts originated in the source 4U 1820-30 in the cluster nucleus, it has been possible to construct a model for the appearance of the events which strongly suggest that the underlying source is a massive black hole (of at least a hundred solar masses). We have since developed a new model[14] which can account for the onset of the bursts and the general behavior of burst sources if they are of mass $\sim 10-100\ M_{\odot}$ (Grindlay 1978, Ap. J., in press). The HXX observations of the second brightest source (4U 1746-37) tentatively identified with a globular cluster resulted in a much reduced (factor of 3 from the Uhuru result) source position error box that includes the cluster nucleus.

The remarkable discovery by ANS of these X-ray bursts prompted the resumption of the ANS pointed observations in March-April 1976. At that time, a search for both steady and burst X-ray emission from globular clusters as well as from the burster MXB 1730-33 was undertaken. No new sources were found among the 16 clusters observed, and significant upper limits and required variability ranges were reported.[15] Bursts were detected from MXB 1730-33,[16,17] and steady emission (but no bursts) was detected from both NGC 6624 and the source A1850-08 near the diffuse globular cluster NGC 6712. The improved ANS position for this latter source is 4 ± 3 arcmin south of the cluster and the combined ANS-Uhuru-Ariel 5 error box (~ 12' x 4') is centered southeast of the cluster and includes several variable stars outside the cluster.[15] However, since the core cannot be excluded, NGC 6712 could resemble the centrally-condensed cluster sources (possibly containing

massive central objects) if the cluster is being disrupted.

Another galactic source discovery involving HXX has been the detection by SXX of X-ray flares of very low luminosity (10^{30} - 10^{31} ergs sec^{-1}) from flare stars.[18] Significant upper limits obtained by both HXX and SXX for a flare detected (by SXX) at 0.25 keV from UV Ceti have been able to limit source models for these events.[19]

The analysis of the spectrum, and spectral variations of 19 strong galactic X-ray sources leads us to propose a new classification scheme for the galactic bulge sources.[20] In 15 of these sources the percentage of total power contained in 1- and 16- second time scale fluctuations varied between 3.2% and 12%, and $\lesssim$ 5% respectively. On time scales of 5, 15, 100, 200 minutes, 1 day, and 6 months, most of the sources showed significant intensity variations. A spectral study has shown that 8 objects favor an exponential-type spectrum: Sco X-1, 4U 1636-53, 4U 1758-20, 4U 1702-36, 4U 1744-26, 4U 1813-14, 4U 1837+04, and 4U 2142+38. Iron line emission at ~6.7 keV has been discovered in 6 and possibly 8 of these same sources: Sco X-1, 4U 1744-26, 4U 1811-17, 4U 1813-14, 4U 1820-30 (high state only), 4U 2142+38, and possibly 4U 1642-45, and 4U 1758-25. Several objects exhibit an intensity-temperature relation similar to Sco X-1, while others are more like Cyg X-1 in their spectral variability. Comparisons of the spectra of the proposed counterparts of 5 X-ray bursters observed indicate they have complex, possibly thermal, spectra which may not include iron line emission during burst activity periods. A new classification scheme is proposed for galactic bulge sources since the spectral and temporal results suggest these objects are either like Sco S-1 (Class 1 GX sources) or like the X-ray bursters (Class 2 GX sources).

A significant result concerning the Orion Nebula was obtained identifying the

X-ray emission region with the center of the nebula.[21]

Although no positive line detection was achieved, the Bragg spectrometer experiment also yeilded significant results in the form of upper limits to the strength of Si XIII and Si XIV line emissions from different types of sources, i.e., a transient X-ray source (A 0620-00), close binary systems (Cyg X-1, X-2, and X-3), supernova remnants (Crab nebula, Cas A, Tycho), GX sources (GX17+2, GX 5-1, 4U 1957+11), and clusters of galaxies.[22] The upper limit of 1.1 eV for the equivalent width of a narrow Si XIV line emission from the X-ray nova A 0620-00 is an order of magnitude lower than previous limits set by other experiments.

B. Extragalactic Sources

The HXX capability for determining source position to within a few arcmin in one dimension has yielded important results on several extragalactic sources of special interest. The position of the X-ray source Cen A was refined considerably from the Uhuru result; the source position is consistent with the nucleas of NGC 5128 and not the inner radio lobes.[23] This position was confirmed by SAS-3. The possible detection of 4U 0138-01 yielded a line of position which suggested this source may be the recently discovered QSO NAB 0137-01, and therefore the most distant X-ray source yet detected.[24]

Finally, an exciting new extragalactic result from HXX/SXX is the fact that in all three observing periods, HXX did not detect the weak source Cyg A (comparable

in flux to NGC 4151, which was detected) whereas the much larger field of view SXX did. This results implies that the source is not the active galaxy Cygnus A, as always assumed, but instead another point source offset by $\gtrsim 6'$ or, more likely, an extended source associated with the cluster of galaxies near Cyg A.[25] A significant improved position for the X-ray source 3U 1921+43 has also been obtained, with an error box of $\sim 7' \times 7'$, centered on the cD galaxy in the galaxy cluster Abell 2319.[26] New radio observations of this galaxy cluster were obtained at Westerbork. The emission at 610 MHz includes several discrete sources and a weak extended component. This strengthens the general association between extended radio halos and X-ray emission from galaxy clusters. The radio halo fills the X-ray error box and is consistent with the new limit reported for the angular size of the X-ray source.

C. Other Results

Finally, a publication was prepared on the cosmic-ray induced environment, as measured by ANS, during its operation.[27] Maps of these radiations, as a function of longitude and latitude, between 200 and 1000 km above the earth, have been generated. They should be extremely useful in the design of future X-ray astronomy experiments.

III. ANS RESULTS PRESENTED AT SCIENTIFIC MEETINGS AND IN PUBLISHED PAPERS

A. ANS Papers at Scientific Meetings

Preliminary X-ray Results from the Astronomical Netherlands Satellite (ANS). H. Gursky, H. Schnopper, E. Schreier, and D. Parsignault. Presented at the 144th Meeting, American Astronomical Society, December 1974.

Probable X-ray Flare of YZ-Canis Minoris Detected by ANS. Presented by J. Grindlay at the Seventh Texas Symposium on Relativistic Astrophysics, December 1974.

The Hard X-ray Experiment On Board the ANS Spacecraft. Presented by H. Schnopper at a meeting of the Dutch Astronomical Society, January 1975.

Preliminary Results of the HXX. Presented by E. Schreier at a meeting of the Dutch Astronomical Society, January 1975.

The Binary X-ray Sources. E. Schreier. Seminar at the University of Amsterdam, January 1975.

Spectral and Time Variations in Cygnus X-3. Presented by D. Parsignault at the COSPAR Conference, May-June 1975.

ANS Observations of Cygnus X-1. Presented by D. Parsignault at the COSPAR Conference, May-June 1975.

First Detection of X-rays from Flare Stars by ANS. Presented by J. Grindlay at the 14th International Cosmic Ray Conference, Munich, August 1975.

Observations of Extragalactic Sources with ANS. Presented by H. Schnopper at the 146th Meeting, American Astronomical Society, August 1975.

X-ray Observations of Cen A and Models for Active Galaxies. Presented by J. Grindlay at a Colloquium, M.I.T. Physics Department, September 1975.

Observations of Cygnus X-1 in Its Two Intensity States by ANS. Presented by D. Parsignault at the Goddard Symposium on X-ray Binaries, October 1975.

Observations of Cygnus X-3 by ANS. Presented by D. Parsignault at the Goddard Symposium on X-ray Binaries, October 1975.

X-ray Spectroscopy With the ANS Satellite. Presented by H. W. Schnopper at the Goddard Symposium on X-ray Binaries, October 1975.

Iron Line Emission in the X-ray Spectrum of Cygnus X-3. Presented by D. Parsignault at the 147th Meeting of the American Astronomical Society, December 1975.

Possible Period for Cyg X-2 Based on Optical, X-ray Data. Presented by E. Wright at the H.E.A.D. (A.A.S.) Meeting on X-ray Astronomy, January 1976.

Limitations on Models of Cygnus X-3 Based on ANS Observations. Presented by D. Parsignault at the H.E.A.D. (A.A.S.) Meeting on X-ray Astronomy, January 1976.

Discovery of X-ray Bursts from Globular Cluster. Presented by J. Grindlay at the H.E.A.D. (A.A.S.) Meeting on X-ray Astronomy, January 1976.

Extragalactic Compact X-ray Sources. Presented by H. Schnopper at the H.E.A.D. (A.A.S.) Meeting on X-ray Astronomy, January 1976.

New ANS Results on Galactic X-ray Sources. Presented by J. Grindlay at the H.E.A.D. (A.A.S.) Meeting on X-ray Astronomy, January 1976.

ANS Observations of X-ray Bursts From the Globular Cluster NGC 6624. Presented by J. Grindlay at the Spring Meeting of the American Physical Society, Washington, D.C., April 1976.

X-ray Burst Sources. Presented by J. Grindlay at the 148th Meeting, American Astronomical Society, June 1976.

Globular Cluster X-ray Sources. Presented by J. Grindlay at the I.A.U. General Assembly, Grenoble, August 1976.

Evidence for Ionized Hydrogen in the Cores of X-ray Globular Clusters. Presented by W. Liller at the 149th Meeting, American Astronomical Society, January 1977.

Thermal Limits for Spherical Accretion and X-ray Bursts. Presented by J. Grindlay at 150th Meeting, American Astronomical Society, June 1977.

B. ANS Publications

1. The Hard X-ray Experiment on the Astronomical Netherlands Satellite. H. Gursky, H. Schnopper, and D. Parsignault 1975, Ap. J. (Letters), 201, L127.

2. ANS Observations of Cyg X-1. D. Parsignault, A. Epstein, J. Grindlay, E. Schreier, H. Schnopper, H. Gursky, Y. Tanaka, A. Brinkman, J. Heise, J. Schrijver, R. Mewe, E. Gronenschild, and A. denBoggende 1975, Astron. and Space Sci., 42, 175.

3. Discovery of Upwards Transition of Cygnus X-1. H. Gursky, J. Grindlay, H. Schnopper, E. Schreier, D. Parsignault, A. Brinkman, J. Heise, J. Schrijver, R. Mewe, and A. denBoggende 1975, I.A.U. Circular 2778.

4. J. Grindlay and E. Schreier 1975, I.A.U. Circular 2863.

5. X-ray Observations of Cygnus X-1 with ANS. J. Heise, A. Brinkman, J. Schrijver, R. Mewe, A. denBoggende, E. Gronenschild, D. Parsignault, J. Grindlay, H. Schnopper, E. Schreier, and H. Gursky 1975, Nature, 256, 107.

6. Preliminary Results on Cygnus X-3 with ANS. A. Brinkman, J. Heise, R. Mewe, A. denBoggende, J. Schrijver, E. Gronenschild, Y. Tanaka, D. Parsignault, J. Grindlay, H. Gursky, E. Schreier, and H. Schnopper 1975, Astron. and Space Sci., 42, 201.

7. On the Stability of the Period of Cygnus X-3. D. Parsignault, E. Schreier, J. Grindlay, and H. Gursky 1976, Ap. J. (Letters), 209, L73.

8. Observational Constraints on the Models for Cygnus X-3. D. Parsignault, J. Grindlay, H. Gursky, and W. Tucker 1977, Ap. J., 218, 232.

9. Intense X-ray Bursts from a Globular Cluster. J. Grindlay and J. Heise 1975, I.A.U. Circular 2879.

10. Discovery of Intense X-ray Bursts from the Globular Cluster NGC 6624. J. Grindlay, H. Gursky, H. Schnopper, D. Parsignault, J. Heise, A. Brinkman, and J. Schrijver 1975, Ap. J. (Letters), 205, L127.

11. Scattering Model for X-ray Bursts: Massive Black Holes in Globular Clusters. J. Grindlay and H. Gursky 1976, Ap. J. (Letters), 205, L131.

12. Discovery of Bursting X-ray Sources. J. Grindlay 1976, Comments on Astrophysics, 6, 165.

13. Globular Cluster X-ray Sources. J. Grindlay 1977, Proceedings of Joint Discussion No. 2, International Astronomical Union, Grenoble, France, in press.

14. Improved Position for the X-ray Source Associated with the Globular Cluster NGC 6441. J.E. Grindlay, H. Schnopper, E. Schreier, H. Gursky, and D. Parsignault 1976, Ap. J. (Letters) 206, L23.

15. X-ray Observations of Globular Clusters with ANS. J.E. Grindlay, H. Gursky, D.R. Parsignault, J. Heise, and A.C. Brinkman 1977, Ap. J. (Letters), 212, L67.

16. ANS Position for Rapid Burst Source. J. Grindlay and J. Heise 1976, I.A.U. Circular 2929.

17. ANS Observations of the X-ray Burster MXB 1730-335. J. Heise, A.C. Brinkman, A.J.F. denBoggende, D.R. Parsignault, J. Grindlay, and H. Gursky 1976, Nature, 261, 562.

18. X-ray Flare from YZ Canis Minoris. J. Heise, A. Brinkman, J. Schrijver, R. Mewe, E. Gronenschild, A. denBoggende, J. Grindlay, H. Schnopper, E. Schreier, H. Gursky, and D. Parsignault 1974, I.A.U. Circular 2731.

19. Evidence for X-ray Emission from Flare Stars Observed by ANS. J. Heise, A. Brinkman, J. Schrijver, R. Mewe, E. Gronenschild, A. denBoggende, and J. Grindlay 1975, Ap. J. (Letters), 202, L73.

20. Intensity and Spectral Variability of Strong Galactic X-ray Sources Observed by ANS. D.R. Parsignault and H. Gursky 1978, Ap. J. submitted for publication.

21. X-rays from the Direction of the Orion Nebula (M 42) with ANS. A. denBoggende, R. Mewe, E. Gronenschild, J. Heise, and J. Grindlay 1977, Astron. and Astrophys., submitted for publication.

22. Si XIII and Si XIV Line Emission Search with the ANS Crystal Spectrometer. D.R. Parsignault, J.P. Delvaille, A. Epstein, J.E. Grindlay, and H.W. Schnopper 1978, Ap. J., submitted for publication.

23. The Location and Intensity of the X-ray Source Centaurus A Observed by the Astronomical Netherlands Satellite. J. Grindlay, H. Schnopper, E. Schreier, H. Gursky, and D. Parsignault 1975, *Ap. J. (Letters)*, *201*, L133.

24. Possible Identification of a High Latitude X-ray Source with a QSO by the Astronomical Netherlands Satellite. E. Schreier, H. Schnopper, H. Gursky, and D. Parsignault 1975, *Ap. J. (Letters)*, *201*, L137.

25. X-ray Observations of Cygnus A with ANS. A.C. Brinkman, J. Heise, A.J.F. denBoggende, J. Grindlay, H. Gursky, and D. Parsignault 1977, *Ap. J.*, *214*, 35.

26. New X-ray and Radio Observations of A 2319. J. Grindlay, H. Gursky, D. Parsignault, A.C. Brinkman, J. Heise, and D. Harris 1977, *Ap. J. (Letters)*, *214*, L57.

27. Radiation Environment Detected by a Proportional Counter in Earth Orbit. D.R. Parsignault, A. Epstein, J. Grindlay, H. Gursky, and H. Cohen 1978, *Astrophys. and Space Sci.*, accepted for publication.